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Determination of the Primordial Helium Abundance from Radio Recombination Line Observations: New Data. The Source W51

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Abstract—Observations of H and He radio recombination lines in the source W51 have been performed with the RT-22 radio telescope (Pushchino) in two transitions: 56α (8 mm) and 65α (13 mm). We have estimated the spectral line parameters and determined the relative abundance of ionized helium, $y^+ = (9.3 \pm 0.35)\%$. We have carried out a model study of the correction (R) for the ionization structure of H II regions (when passing from the observed $y^+ = N(\mathrm{He}^+)/N(\mathrm{H}^+)$ to the actual $y = N(\mathrm{He})/N(\mathrm{H})$) as a function of the spectral type of the ionizing star. Hence it follows that it is desirable to choose the sources excited by hot stars of spectral types no later than O6 V to estimate the helium abundance. In this case, the correction is expected to be small and essentially constant, R in the range 1.0–1.05. We have analyzed the correction for the ionization structure of W51, obtained an actual abundance of helium in the range $y = (8.9–9.7)\%$, and determined its primordial abundance Y_p (produced during primordial nucleosynthesis in the Universe) in this source. We have made a new estimate of the primordial helium abundance from six Galactic H II regions, where we observed H and He radio recombination lines at different times. The weighted mean $Y_\mathrm{p} = 25.64(\pm 0.70)\%$ has been obtained. On the one hand, this value of Y_p does not yet disagree strongly with the conclusions of the standard cosmological model, but, on the other hand, it admits the existence of at least one unknown light particle in the period of primordial nucleosynthesis outside the scope of the standard cosmological model. One should continue to refine Y_p for more reliable conclusions to be reached.

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INTRODUCTION

Measuring the primordial helium abundance, $Y_\mathrm{p} = (^4\mathrm{He}/\mathrm{H})$, produced during primordial nucleosynthesis is very important for modern cosmology. In addition to ^{4}He, several more elements were produced during primordial nucleosynthesis (within the first 2–3 min after the Big Bang): deuterium, ^{3}He, tritium, and ^{7}Li. However, whereas their yield depended only on the baryon density of the Universe, the helium yield depended to a greater extent on the neutron/proton (n/p) freeze-out conditions. One of these conditions was the number of light, relativistic particles (see, e.g., Klapdor-Kleingrothaus and Zuber 1997) at the freeze-out time (~10–20 s after the Big Bang). Thus, whereas the above elements are indicators of the baryon density of the Universe, the primordial helium abundance is also an indicator of the presence or absence of unknown light particles. The contribution from known light particles is well calculated in terms of the standard cosmological model (SCM) (Klapdor-Kleingrothaus and Zuber 1997). The presence of unknown light particles may imply a deviation from the SCM.

In most works, Y_p was estimated from recombination lines in the optical wavelength range, where a linear relationship was established (see, e.g., Izotov and Thuan 2004) between the observed helium abundance ($Y = \mathrm{He/H}$ by mass) and the abundance of heavier elements (Z):

$$Y = Y_\mathrm{p} + Z dY/dZ. \quad (1)$$

This is explained by the fact that both some amount of helium and an overwhelming amount of heavier elements are synthesized in stars during their evolution. Y_p is usually sought for from the observed dependence $Y(Z)$ when Z is extrapolated to zero by assuming that $Z = 0$ in the early Universe.

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Optical observations are known to be subject to numerous systematic effects, which impose constraints on the result being obtained (see, e.g., Pagel 2000; Izotov et al. 2007; Tsivilev 2009; Porter et al. 2009; Aver et al. 2010). Ideally, the statistical errors can be reduced to zero, while the systematic errors stop the advancement in accuracy.

Radio measurements have their advantages. They require no model calculations of level population coefficients, because helium at high excitation levels (with a principal quantum number of ~50 or larger) is a hydrogenic system. Therefore, the population coefficients for identical helium and hydrogen levels are identical and cancel out in the (He/H) ratio, and we directly measure $N(\mathrm{He}^+)/N(\mathrm{H}^+)$. Thus, measurements from radio recombination lines (RRLs) are free from an overwhelming number of problems of optical measurements and can give independent, additional information about the helium abundance in the interstellar medium and about primordial nucleosynthesis.

Previously (Tsivilev 2009), we described in detail a method for measuring Y_p from RRLs and obtained $Y_\mathrm{p} = 25.2–25.5\%$ with an error of $\pm 0.9\%$. On the one hand, such a value, within the error limits, does not reject the conclusions of the helium yield calculations in the case of primordial nucleosynthesis based on the SCM; on the other hand, it admits a deviation from the SCM in the sense of the existence of unknown light particles. The succeeding new estimates in the optical range (Izotov and Thuan 2010; Aver et al. 2010; Skillman et al. 2012) strengthened the conclusion about a "high" value of Y_p that makes the existence of unknown light particles during primordial nucleosynthesis possible. For example, in Izotov and Thuan (2010), the estimate of Y_p exceeds Y_p obtained within the SCM at the 2σ level.

Recently, however, having analyzed and selected the Izotov–Thuan data, Aver et al. (2012) concluded that Y_p is still consistent with the SCM, within the error limits.

The goal of this paper is to improve the estimate of Y_p from RRLs obtained previously (Tsivilev 2009). An improvement was achieved through the following factors:

(1) Observations of RRLs in the source W51 were performed in two transitions: 56α (8 mm) and 65α (13 mm). This increased the number of sources where we measured the relative helium abundance from RRLs.

(2) A more accurate slope of the dependence $Y(Z)$ (1), $dY/dZ = 1.62(\pm 0.29)$, was obtained from optical measurements (Izotov and Thuan 2010).

(3) We carried out a new study of the influence of the ionization structure on measuring Y_p.

We describe our observations of H and He RRLs in W51 and our model studies of the correction of the measurements of the relative helium abundance $N(\mathrm{H})/N(\mathrm{He})$ for the ionization structure of H II regions. We then obtain and discuss a new estimate of Y_p from RRLs. In conclusion, we list our conclusions.

RLL OBSERVATIONS IN W51

We performed our observations of H, He, and C RRLs with the RT-22 radio telescope (FIAN) in two transitions, 56α (8 mm) and 65α (13 mm), by the ON–ON method (Berulis et al. 1983) by ~7 min scans. The data of each scan were calibrated to the antenna temperature and were corrected from the atmospheric absorption. Subsequently, we obtained the mean spectra over days and then the means between days and sessions, accumulating the signal for tens of hours (Tsivilev 1998). We used an autocorrelation spectrum analyzer with 2048 channels and a frequency band width of 50 MHz. The spectral line parameters in the resulting spectrum were determined by the rms approximation of the spectra (fitting) by the maximum-neighborhood method (Smirnov and Tsivilev 1982; Tsivilev 1998). Figure 1 presents our spectra, and Table 1 gives the derived spectral line parameters and some of the results. The columns of the table list: RLLs, the line amplitude in antenna temperatures, the full width at half maximum of the lines, and the radial velocity; the last column gives the derived electron temperatures under the assumption of local thermodynamic equilibrium (LTE) and the relative abundance of ionized helium $\mathrm{y}^+ = N(\mathrm{He}^+)/N(\mathrm{H}^+)$ obtained as the ratio of the integrals of the He and H lines.

The source's coordinates are $\alpha(1950) = 19^\mathrm{h}21^\mathrm{m}24.4^\mathrm{s}$ and $\delta(1950) = 14°24'48''$. The beam width of the RT-22 radio telescope is $\varphi \approx 2.0'$ at 8 mm and $\varphi = 2.6'$ at 13 mm.

For the 56α transition, we found an insignificant dependence of the fit on the model of the spectrogram's zero line. This leads to a small (~0.2%) systematic error in y^+, which is marked in the table. Taking this into account, we will obtain the weighted mean from two transitions (56α and 65α), $y^+ = (9.3 \pm 0.35)\%$.

In our observations, one of the problems was the distortion of the spectrometer's zero line due to the interference of noise and the received signal, predominantly during their reflection between the main mirror and the subreflector of the radio telescope; the distortions are quasi-sinusoidal in shape (Bakhrakh et al. 1963; Bania et al. 1987) with a period dependent on the separation between the reflecting surfaces (for RT-22, ~15 MHz). The amplitude of this spurious

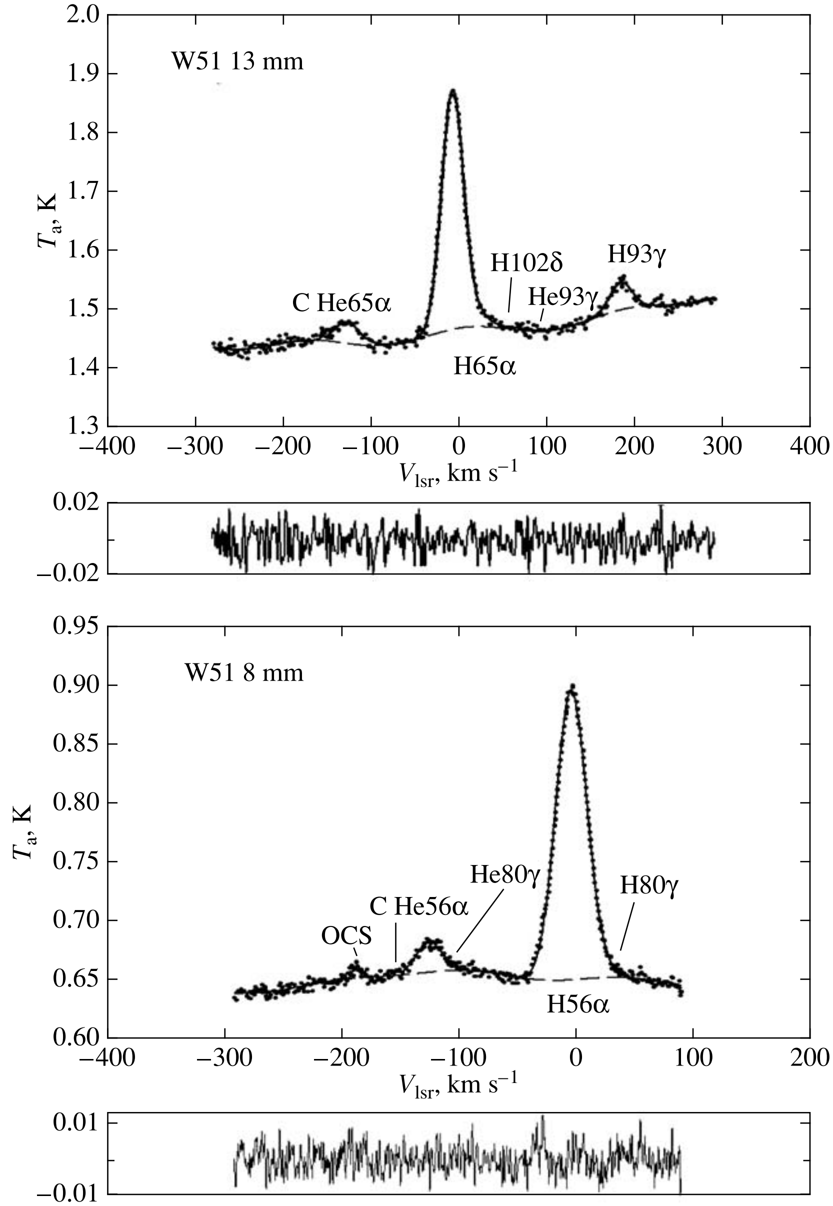

Fig. 1. RT-22 spectra: at 13 mm (top) and 8 mm (bottom). Zero corresponds to $V_{lsr,0} = +58.0$ km s^{-1} for the H line. The solid curve indicates the fitted line profile; the dashed curve marks the zero line (the continuum level). The difference of the derived and fitted spectra is shown under each plot in the same units.

signal in individual series of observations was comparable to the amplitude of the helium line, and y^+ could be underestimated if the He line fell into the trough of the zero line and overestimated if it fell on the peak.

One of the methods for combatting this distortion is compensation through an alternation of subreflector (hyperbola) shifts by $\pm\lambda/8$ (Bania et al. 1987). We investigated this method and found, as in our previous paper (Tsivilev 1998), that the effect of this method was negligible. However, the distortion amplitude clearly decreases when averaging the observational data for widely separated dates obtained in different seasons of the year.

This can be explained in part as follows. Because of the Earth's orbital motion around the Sun, the spectral line position is shifted relative to the spurious signal. Since the frequency of observations was set in such a way that the spectral line was in the same channel, the spurious signal was shifted relative to the line and was averaged with different phases when averaging the spectra of different dates, which caused its amplitude to decrease. Therefore, our present observations, as the previous ones, were carried out

Table 1. Results of our observations of RRLs in W51

RRL	Amplitude, K	ΔV, km s^{-1}	$V_{\rm lsr}$, km s^{-1}	Obtained
H65α	.411 (.0023)	29.97 (.23)	57.0 (.12)	$T_e = 6540\,(500)$ K
He65α	.0371 (.0013)	32.35 (1.4)	56.9 (.46)	$y^+ = 9.74\,(0.55)\%$
H93γ	.0471 (.0013)	30.4 (1.0) fix	60.9 (.34)	
C65α	.0112 (.0036)	2.3 (0.8) fix	56.4 (.36)	
H56α	.2314 (.0009)	30.02 (.11)	55.6 (.03)	$T_e = 8200\,(420)$ K
He56α	.0244 (.0008)	25.4 (0.82)	56.5 (.25)	$y^+ = 8.94\,(0.40)\%$ (0.20 sys)%
C56α	.003 (.0009)	5.8 (2.4)	55.2 (.9)	

Note. $V_{\rm lsr}$, apart from the random error given in parentheses, there is a systematic error of ~0.2 km s^{-1}; fix—fixing the parameter when fitting.

(with or without the hyperbola motion) in several sessions (with a duration of ~10 days) in different seasons of the year. The residual spurious signal was compensated when fitting our spectra by introducing sinusoidal terms into the fitting function to describe the zero line of the spectrograms (Tsivilev 1998).

According to the RRL theory (Sorochenko and Gordon 2003), the line shape was described by a Gaussian profile.

MODEL STUDY OF THE CORRECTION FOR THE IONIZATION STRUCTURE OF H II REGIONS

At radio frequencies where the optical depth is less than unity (as in our case), the helium abundance measured from RRLs, $y^+ = N(\mathrm{He}^+)/N(\mathrm{H}^+)$, and the actual abundance, $y = (N(\mathrm{He})/N(\mathrm{H}))$, can be related by some structure factor R:

$$N(\mathrm{He}^+)/N(\mathrm{H}^+) = RN(\mathrm{He})/N(\mathrm{H}) \qquad (2)$$

or

$$y^+ = Ry.$$

The factor R reflects the influence of the ionization structure of an H II region on the y estimate (the ratio of the sizes of the H$^+$ and He$^+$ zones and their emission measures) and is determined by the properties of the ionization source (mainly by the effective stellar temperature $T_{\rm eff}$) and the source's structure.

We carried out model studies of the correction factor R as a function of the effective stellar temperature ($T_{\rm eff}$) for various model stellar atmospheres. We considered the model of a spherically symmetric H II zone composed of hydrogen, helium, and dust with a drop in density from the center characteristic of Orion A (Tsivilev et al. 2010). The input parameters of the model were the radiation from the central star (the ultraviolet flux as a function of the frequency), the density distribution, the dust content, and the relative abundance of H and He: $N(\mathrm{He})/N(\mathrm{H})$. The H and He ionization fractions were determined from the system of ionization balance equations (Osterbrock 1989; Ershov et al. 1998), which was solved numerically by the method of simple iterations (Ershov 1995). The influence of the metastable level of helium and dust was rigorously taken into account. We derived the distributions of the He and H ionization fractions with distance from the center of the H II zone. Subsequently, we calculated the total RRL intensities $I(\mathrm{H})$ and $I(\mathrm{He})$ by assuming the entire H II zone to be within the beam of the radio telescope. We obtained the "observed value" of $N(\mathrm{He}^+)/N(\mathrm{H}^+) = I(\mathrm{He})/I(\mathrm{H})$. Comparing this value with the specified $N(\mathrm{He})/N(\mathrm{H})$, we determined the factor R. All of the ionizing photons were also assumed to be absorbed within the nebula (the H II region is bounded by ionization). The H and He RRL intensities were calculated for the 56α transition.

We considered main-sequence stars and investigated several most popular model stellar atmospheres: Kurucz-79 (Atlas, New Atlas), WM-Basic, Tlusty, they were all taken from the Cloudy site (http://wiki.nublado.org/ wiki/StellarAtmospheres), and (LTE and non-LTE) models from Mihalas (1972). The calibration of stars (spectral type—$T_{\rm eff}$) was taken from Massey et al. (2005).

The results of our calculations are presented in Fig. 2. The main conclusion is that the dependence of the structure factor R on $T_{\rm eff}$ has two characteristic segments.

(1) For stars with $T_{\rm eff} \geqslant 38\,000$ K (stars of spectral type $\leqslant$O6), the factor R is essentially constant (see Fig. 2), $R \approx 1.0$–1.05, irrespective of the model stellar atmosphere. RRL observations in nebulae with such stars make it possible to directly measure the helium abundance $N(\mathrm{He})/N(\mathrm{H})$. This is because the

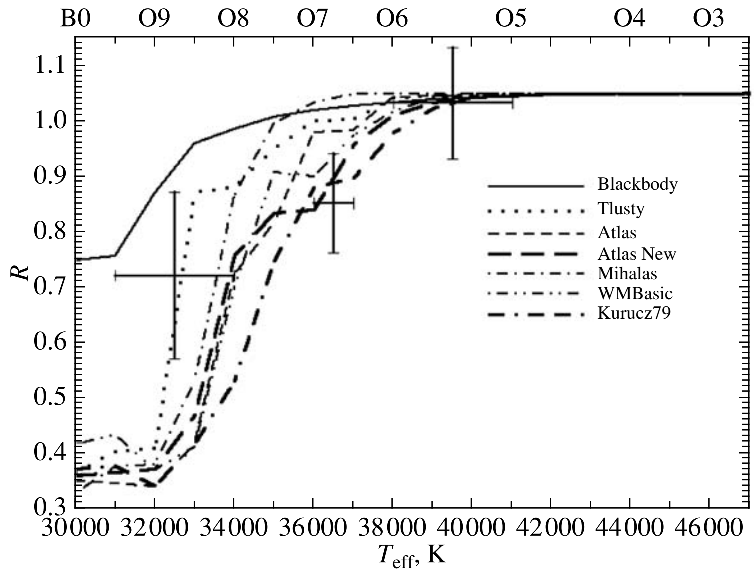

Fig. 2. Calculated factor R for an H II region with a variable density versus T_{eff} of the exciting stars or their spectral type. The crosses mark approximate experimental data for the sources NGC 2024, Ori A, and W3A.

sizes of the He and H ionization zones for hot stars are close or there is an inversion of the zones: the He II zone can go beyond the H II zone. However, in the case of inversion, the He II zone cannot go far away from the H II zone, because the amount of neutral hydrogen increases sharply in the transition region, which begins to efficiently compete with helium in the absorption of stellar photons capable of ionizing helium. As a result, R becomes essentially constant. The influence of dust manifests itself as a decrease in the sizes of the ionization zones; the H ionization zone is reduced more dramatically than the He ionization zone, because dust absorbs the hydrogen-ionizing photons more efficiently (see, e.g., Aannestad 1989); as a result, the passage of R through 1.0 and the zone inversion occur at lower temperatures T_{eff} than it would be in the absence of dust.

(2) For cooler stars, i.e., those of spectral type >O6V, the factor R depends on the specific model stellar atmosphere and its T_{eff} and can change from 0 to 1. Good data on the star and the H II region and model calculations are needed.

In principle, benefit can also be gained in this segment: either we can reach a rough conclusion about the ionizing star if it is unknown or by comparing the observed value of $N(\mathrm{He}^+)/N(\mathrm{H}^+)$ and the calculated one for a source with a star of known spectral type, we can reach a conclusion about the acceptability of a particular model stellar atmosphere and its calibration. For example, the crosses in Fig. 2 indicate possible values of R for the sources NGC 2024, Ori A, and W3A based on Table 2 as $R = y^+/y_{\mathrm{o}}$, where y_{o} is $N(\mathrm{He})/N(\mathrm{H})$ averaged over the measured values. The data on NGC 2024 were taken from Sorochenko and Tsivilev (2000).

It can be seen that so far all of the above model stellar atmospheres, except the blackbody case, must not be ruled out.

DATA ANALYSIS, A NEW ESTIMATE OF Y_{p} FROM RRL, AND DISCUSSION

W51

Our analysis of the hydrogen RRL shape in W51 shows that it can have a two-component structure. With a high probability, this is the intersection of two bright components of the source W51A, known in the literature as components e (strongest) and d, within the diagram. Table 3 gives their continuum flux densities.

Berulis and Sorochenko (1972) found the total flux density at 8 mm to be ∼72.4(5) Jy. The source is optically thin in the frequency range 22–36 GHz, i.e., the flux density of component e depends on frequency as $S \sim v^{-0.1}$: it is 55 Jy at 22 GHz and ∼52 Jy at 36.5 GHz. Consequently, component d can have a flux density of ∼20 Jy at 8 mm.

Under these conditions, the estimate of the relative helium abundance $y = N(\mathrm{He})/N(\mathrm{H})$ based on our measured $y^+ = N(\mathrm{He}^+)/\mathrm{N}(H^+)$ becomes more complicated. It will consist of two parts:

$$y^+ = R(\mathrm{e})y + kR(\mathrm{d})y, \quad (3)$$

where k is the weight of component d as the ratio of the flux densities from components d and e, and R(e, d) is the structure factor of components e and d. It can

Table 2. Results of our Y_p determination from Galactic H II regions

Source	$N(He^+)/N(H^+)$, %	Δy(IS), %	N(He)/N(H), %	Z(metallicity)	Y_p, %
Orion A		See [1]	10.0 (0.8)	0.0112 (.0022)	26.44 (1.7)
W3A	9.9 (0.5)	−0.6	9.3 (0.5)	Distant	26.1 (1.5)
M17	11.1 (1.1)	−0.7	10.4 (1.1)	0.0183 (.0018)	25.88 (2.2)
NGC 7538	8.1 (0.8)	See [1]	8.9 (.9)	Distant	25.15 (2.1)
W48	9.6 (1.3)	∼0.0	9.6 (1.3)	0.0183 (.0019)[m]	23.78 (∼3.0)
W51	9.3 (0.35)	See text	8.9–9.7 (.34–.36)	0.00967 (0.0021)	25.35 (1.17)

Note. Distant is the external source, m is the model value of Z over the Galaxy (Tsivilev 2009), [1]—(Tsivilev 2009).

Table 3. Ratio of the flux densities (Jy) for components d and e in W51

Component	36.5 GHz (8 mm)[c]	22.4 GHz (13 mm)[b]	8.3 GHz (3.6 cm)[a]	∼5 GHz (6 cm)[a]	1.4 GHz (20 cm)[a]
d	∼20	36	10	8.6	∼4.5
e	∼52	55	42	47	∼31

Note. [a]—the data from Mehringer (1994); [b]—the data from Wilson et al. (1979); [c]—the data from Berulis and Sorochenko (1972).

be seen from Table 3 that the d/e flux density ratio at high frequencies may be expected in the range 0.38–0.65.

For a more proper estimate, we decided to perform model calculations of the total profile for RRLs from the two components and to determine R. The parameters of the ionizing stars should be known for these calculations. As regards component e, the situation is relatively simple. It can be seen from the maps (see, e.g., Fig. 2 from Figueredo et al. (2008)) that the central part of W51 containing components d and e is ionized (at least) by stars #44 and #50 of spectral types O5.0V and O6.5V, respectively. According to our calculations (Fig. 2), R(e) may be expected to reach ≈1.05 here, where there are hot stars of spectral type ⩽O6.

The situation with component d is more confused. Figueredo et al. (2008) believe that O-type stars are present there, but they do not report precisely which stars. Okamoto et al. (2001) studied this question in more detail; for the brightest star of component d, they found the range O5.5–O9V. Unfortunately, this is a large uncertainty; according to our calculations, it admits R in the range 0.4–1.05 with a mean of ∼0.73.

We performed a two-component fitting of our H, He 56α RRL spectrum and obtained the following values of y^+: 9.4–10.0% for component e, in agreement with R close to unity; and 5.8–7.5% for component d, suggesting that $R < 1$ there. (Since the errors in the RRL parameters and, consequently, y^+ increase in the case of two-component fitting, we do not take this result as a basis but use it only for information.)

In their more recent paper, Barbosa et al. (2008) argue that the source of ionization of the source IRS2 (component d) is a star of spectral type O3–O4 at a distance of 5–8 kpc to the source. However, this is already inconsistent with our "small" estimates of y^+ for this component.

Consider two extreme cases. In the first case, component e is ionized by a hot star ($R(\mathrm{e}) \geqslant 1$), while component d is ionized by a cool one ($R(\mathrm{d}) < 1$). In the second case, both components are ionized by hot stars. From Eq. (3), we can obtain $R = 0.96$ and 1.05 for these cases. For a more careful justification, we performed model calculations of the factor R by taking for the first case a hot star with $T_{\mathrm{eff}} = 42\,000$ K (component e) and a cool star with $T_{\mathrm{eff}} = 33\,900$ K (component d) ($R(\mathrm{d}) \approx 0.7$). The electron temperatures of nebulae e and d were assumed to be 7400 and 6800 K, respectively; the radial velocity difference between the components is 2.6 km s^{-1} (Van Gorkom et al. 1980). In the second case, both components had a hot star with $T_{\mathrm{eff}} = 42\,000$ K. We obtained a model value of $R = 0.974$ in the first case and $R \approx 1.0$ in the second case. For comparison, we made independent estimates using the code from the cloudy site (version 13.01; Ferland et al. 2013) and obtained $R = 0.96$ and $R = 1.0$ for the first and second cases, respectively.

Our analysis shows that R is close to unity with a spread of 0.96–1.05. To take into account the entire interval, we estimated the helium abundance for the extreme values.

Thus, in the first case, we will obtain the actual helium abundance $y = (9.69 \pm 0.36)\%$ and determine (Tsivilev 2009) $Y_{\rm p} = 0.2793(1 - Z) - 1.62Z = 26.09(\pm 0.9)\%$.

To estimate the heavy-element abundance Z (metallicity), we use the oxygen abundance (O/H) measured by Rudolph et al. (2006), who obtained $12 + \log(\mathrm{O/H}) = 8.61\,(+0.02, -0.16)$ for W51. Given that part of the oxygen can be in dust grains, up to 0.12 dex (Carigi and Peimbert 2010), and taking $Z = 18\mathrm{O/H}$, we obtain $Z = 0.009667\ (\pm 0.0021)$ for W51.

In the second case, $y = 8.86 \pm 0.34\%$ and $Y_{\rm p} = 24.60(\pm 0.9)\%$. We use a new slope of the dependence $Y(Z)(1)$, $dY/dZ = 1.62(\pm 0.29)$ (Izotov and Thuan 2010).

Thus, the result of our estimation in the two cases can be written as

$$Y_{\rm p} = 25.35(\pm 0.9\ \mathrm{stat})\ (\pm 0.75\ \mathrm{sys})\%.$$

The summary Table 4 presents the results of our primordial helium estimation from Galactic sources (Tsivilev 2009) using the new value of dY/dZ.

As a result, we obtain the weighted mean of the new estimate $Y_{\rm p} = 25.64(\pm 0.70)\%$ from RRLs.

DISCUSSION

Our RRL (8–13 mm) measurements were made within an optimal wavelength range, where, on the one hand, the optical depth effects are small, the Stark line broadening is small, etc. and, on the other hand, the deviations of the helium level populations from hydrogenicity do not yet manifest themselves. Previously (Tsivilev 2009), we analyzed in detail possible errors and problems. It can be noted that we think two problems to be most significant: the distortions of the spectrometer's zero line during observations and the correction for the ionization structure of H II regions when calculating $N(\mathrm{He})/N(\mathrm{H})$.

Above (see the Section "RRL observations in W51"), we described the method for combatting the distortions of the zero line. Note that during long-term observations by individual sessions, the distortions of the zero line can be below the noise level, as was the case for W3A (Gulyaev et al. 1997). As regards the correction for the ionization structure, as it was shown above, we should try to choose the H II regions excited by hot stars of spectral types no later than O6. It should be kept in mind that H II regions are not always bounded in ionization; occasionally (for example, as in Orion A; Poppi et al. 2007), some of the stellar ultraviolet photons can go outside the H II zone. In this case, R will decrease to $\sim$1. Thus, for hot stars, R will be in the range 1.0–1.05.

Another possibility to somehow obtain information about the ionization structure is, for example, to map the source in H and He RRLs. The latter is highly desirable for stars cooler than O6V. The extent to which the correction is needed can be estimated by comparing the derived value of y^+ with the expected minimum value obtained from angular cosmic microwave background (CMB) anisotropy measurements. According to the latest data, the expected amount of primordial helium ($Y_{\rm p}$) is in the range 24.76($\pm$.04)–24.87 ($\pm$0.02)% (Coc and Vangioni 2010; Skillman et al. 2012). This corresponds to the range 8.23–8.28% by the number of particle (y). It should be taken into account that some amount of helium is additionally synthesized by galactic stars, $\sim$1% by the number of particles (Hoyle and Teyler 1964). For our estimate, we will take half of the stellar contribution, 0.5%. Thus, if the observed value of y^+ is less than 8.7–8.8%, then this may imply that the nebula is excited by a star of a later spectral type than O6, and studies should be carried out to find the correction for the ionization structure. (For inner galactic sources, this criterion can be higher.)

In any case, for more accurate estimates, it is desirable to perform model calculations of R. This requires reliable information about the ionization source (a star or a group of stars, their spectral type), which is not always possible. The problems of choosing and calibrating model stellar atmospheres are superimposed on this. Further progress in theoretical and observational astrophysics can improve the situation. For the sources discussed here, the problem of R to some extent has been solved.

A few words should be said about dY/dZ. Previously (Tsivilev 2009), we took the range of values 2.2–2.8; as a consequence, we obtained the range of $Y_{\rm p}$ estimates (25.5–25.2%). After the publication of the paper by Izotov and Thuan (2010), where $dY/dZ = 1.62(\pm 0.29)$ was refined based on a significant sample of sources (86), we took this value as a basis. However, it should be noted that our estimates (with regard to inner galactic sources) depend on this quantity. If serious arguments will appear in future for a different value of this quantity, then our estimates of the primordial helium abundance will also change. For example, Aver et al. (2012) believe that dY/dZ lies in the range 1–3. However, having a large error, their measured values of 2.7 ± 5.0 agree with many of the values, including those from Izotov and Thuan (2010). Smaller dY/dZ increase our estimate of $Y_{\rm p}$ and vice versa. Moreover, the value obtained by Izotov and Thuan agrees better with theoretical studies (Langer and Henkel 1995; Larsen et al. 2001) than

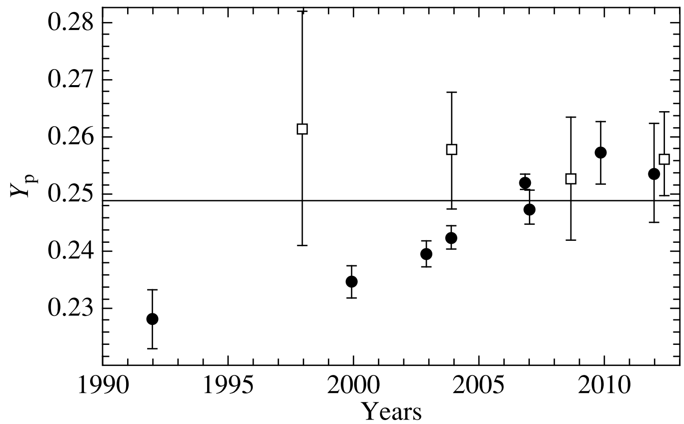

Fig. 3. Dynamics of the Y_p estimation in the last 20 years: the circles and squares mark the optical data and our estimates from RRLs, respectively. The figure was taken from Peimbert (2008) and supplemented by subsequent optical estimates: Izotov and Thuan (2010), Skillman et al. (2012), and Aver et al. (2012). The RRL data: Tsivilev (1998), obtained from one distant source without using dZ/dY; Tsivilev et al. (2004), $dZ/dY = 2.3$; Tsivilev (2009), $dZ/dY = 2.2–2.8$; this paper, $dZ/dY = 1.62$. The horizontal straight line marks Y_p obtained within the SCM based on measurements of the baryonic density of the Universe from the CMB anisotropy (Peimbert 2008).

do larger values. Therefore, the dY/dZ measurements by Izotov and Thuan (2010) are most accurate, were obtained from a larger number of sources, are consistent with the latest data, and agree well with theoretical studies.

Figure 3 presents the primordial helium abundance determinations in the optical range and our estimates from RRLs in the last ~20 years. Whereas previously the optical and RRL data disagreed, in recent years they have come to agreement: Y_p is close to or slightly higher than ~25%. Such a value admits the existence of unknown light (relativistic) particles during primordial nucleosynthesis in the Universe, i.e., a deviation from the SCM. On the other hand, within the measurement error limits, it does not disagree strongly with the SCM conclusions. Therefore, further measurements, especially those from RRLs, where there are fewer systematic problems, are needed.

By comparing the derived value of Y_p with its estimates from angular CMB anisotropy measurements (see, e.g., Coc and Vangioni 2010), we can estimate the additional (more than three) unknown number of neutrino-type light particles (Tsivilev et al. 2004; Tsivilev 2009):

$$\Delta N = (Y_p - 0.2476)/0.013, \tag{4}$$
$$\Delta N = 0.1-1.2,$$

i.e., the existence of at least one light particle is admitted. At present, as yet there is no evidence for the possibility of the existence of unknown light particles within the existing paradigm, but this does not mean that this problem should not be addressed. For example, the reports that a previously unknown, relatively light particle (with a mass of ~38 MeV) can exist have appeared (Abraamyan et al. 2012).

CONCLUSIONS

We performed observations of RRLs in W51 in two transitions: 56α (8 mm) and 65α (13 mm). Spectral line parameters and some results were obtained: T_e (LTE) and the relative helium abundance $y^+ = 9.3 \pm 0.35\%$.

We carried out a model study of the correction for the ionization structure of H II regions when passing from the observed y^+ to the actual $y = N(\mathrm{He})/N(\mathrm{H})$ as a function of the spectral type of the ionizing star. Hence it follows that it is desirable to choose the sources excited by hot stars of spectral types no later than O6. In this case, the correction is expected to be small and essentially constant, R in the range 1.0–1.05.

We analyzed the correction for the ionization structure of W51, based on which we obtained an actual abundance of helium in the range $y = 8.9–9.7\%$ and determined its primordial abundance:

$$Y_p = 25.35(\pm 0.9 \text{ stat}) \ (\pm 0.75 \text{ sys})\%.$$

We made a new estimate of Y_p from six Galactic H II regions, where we observed H and He RRLs at different times. We obtained the weighted mean

$$Y_p = 25.64(\pm 0.70)\%.$$

On the one hand, such a value of Y_p does not yet disagree strongly with the SCM conclusions, but, on the other hand, it admits ($\Delta N > 3$) the existence of at least one unknown light particle in the period of primordial nucleosynthesis.

In any case, we should continue the work and improve Y_p in order to reconcile it with the SCM or to strengthen the conclusion about the derived excess ΔN.

It should be noted that other explanations can also exist (Tsivilev et al. 2004) for the "high" value of Y_p, for example, the existence of primordial, giant, and rapidly evolved stars if, of course, they could produce more helium compared to other elements than is done by ordinary stars.

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